PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	
Jagiella, et al.	Examiner: H. Pham
Serial No.: 10/047,447	Art Unit: 2877
Filed: January 14, 2002	

For: **SENSOR DEVICE FOR BURR EXAMINATION**

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Signature: Carol Prentice
Carol Prentice

DECLARATION UNDER 37 C.F.R. § 1.132

We, Manfred Jagiella and Dr. Sorin Fericean, declare that:

1. We are the Applicants in the above-identified U.S. patent application (referred to herein as "the present application"), and the inventors of the invention disclosed and claimed therein.

2. The present application claims priority from German patent application no. 101 03 177.7 filed on January 22, 2001.

3. We are, and at the time of conception of the present invention were, employed by Balluff GmbH, a German limited liability company, the assignee of the present application.

4. The invention claimed in the present application satisfies a long felt need in the industry for a burr examination device that allows a non-time-consuming examination of burrs and that also allows quantitative information content about burrs to be inferred.

5. A burr is often created during cutting operations in any phase of manufacturing, such as when drilling holes through engine blocks or producing drive shafts. The degree of burr formation depends on, among other things, the material of the cutting tool (e.g., drills, end milling cutters, and the like), the machining parameters, and the composition of the workpiece. These factors may even vary during series production.

6. The presence of a burr can cause a variety of problems as is well known in the art of manufacturing. For example, burrs may represent a potential for injury during handling, may affect the flow of oil on parts in the drive area, or may break off and cause premature wear.

7. To avoid the problems associated with burrs, many parts are 100% deburred. In the case of quality dependent parts (e.g., injection nozzles in a common rail system, gear shafts, and the like), manual quality inspection of the part is usually required to ensure that workpieces are absolutely free of burrs. Manual burr examinations may comprise, for example, feeling a corresponding workpiece surface with a finger, a finger nail, a tooth pick, a cleaning tube of cotton wool lining, a tip of a pencil or a marker mandrel. Visual methods have also been used where, for example, a burr is examined with the naked eye, under a microscope or by means of a magnifying glass, an autoscope, or by means of an endoscope. Such an examination is extremely difficult to accomplish in parts having interior hole intersections. Further, the costs for deburring and for manual burr inspection can amount to several percent of the cost of the part.

8. Accordingly, there was a long felt need in the art for a universal, industrial quality measuring system for inspection and qualitative assessment of burrs which could be integrated into a production process.

9. As a result of this long felt need, the Burr Minimization Industry Workgroup (the "Workgroup") was founded at the end of 1999. Participants in this Workgroup included automobile manufacturers and automotive suppliers, such as Daimler-Chrysler, BMW, VW, Audi, Porsche, Ford, Bosch, ZF, and others, as well as scientific institutions such as the University of California at Berkley, the IPA (Institut für Produktionstechnik und Automatisierung) in Stuttgart Germany, The FBK (Fertigungstechnik und Betriebsorganisation) at the University of Kaiserslautern, and the FHTW (Fachhochschule für Technik und Wirtshaft) in Berlin.

10. In 2001, Balluff GmbH, the assignee of the present application, joined the Workgroup with the goal of developing an inspection and measuring system for burrs that would solve the problems and satisfy the long felt need in the industry noted above.

11. We developed the present invention as a result of Balluff GmbH's involvement in the Workgroup. The present invention, as currently claimed, provides a burr examination sensor device for the examination of burrs on a workpiece. The sensor device comprises at least one distance sensor with a detector head. The detector head is positionable at a distance to the workpiece. The detector head and the workpiece are movable relative to one another. The detector head has an active surface that is electromagnetically couplable to the workpiece via at least one of inductance or capacitance, for determining a distance between the detector head and the workpiece by scanning a workpiece surface with the active surface of the detector head in order to detect variations in at least one of inductance and capacitance indicative of burrs, without any contact between the active surface and the workpiece surface.

12. As a result of the use of a distance sensor, the burr examination can be carried out in a simple manner. The active surface of the detector head of the distance sensor forms a sensor field that is coupled locally to the workpiece. As a result, inner workpiece surfaces may also be examined when the distance sensor is inserted into the workpiece. The coupling of the distance sensor to the workpiece is influenced by the distance between the active surface and the workpiece surface. As the presence of a burr alters this distance, not only can the presence of the burr be detected, but quantitative information regarding the burr can be obtained, such as the amount of extension of the burr and the type of the burr.

13. The burr examination carried out with the claimed invention takes place without any contact such that a simple and, in particular, mechanical use is facilitated. Further, the influence of soiling (e.g., by oil, lubricants, or contamination) is also reduced with the claimed invention, since any soiling of the workpiece or sensor has an effect, at the most, on the local sensor field.

14. Our paper entitled "Inductive Sensor System for Evaluation of Burrs and Edges in Industrial Applications" presented at the 7th International Conference on Deburring and Surface Finishing CODEF at the University of California, Berkeley, is attached as Exhibit A. This paper describes, in more detail than set out above, the formation of burrs, problems associated with burrs, prior art methods of burr detection, and deficiencies in such prior art burr detection. Our paper, Exhibit A, further describes the present invention in sections V and VI thereof, and sets forth successful experimental and field test results at section VII thereof.

15. In 2002, Daimler-Chrysler purchased the first system produced in accordance with the claimed invention for testing purposes. Successful practical testing was carried out on a test stand for drive shafts used in the Daimler-Chrysler A-Class vehicles.

16. Accordingly, the claimed invention overcomes problems with burr examination that have not been solved by others, while also satisfying a long felt need in the industry.

17. In addition, the claimed invention has received a warm welcome and has been appreciated in the field.

18. The Workgroup presently has plans to standardize the measuring process used with the claimed invention throughout the industry.

19. The present invention was selected by R&D magazine as one of the one hundred most technological significant new products of the year 2003, Exhibit B.

20. The present invention also received the "AutoTec Award 2003" as best innovation in automotive technology for 2003 by the International Institute for Research, Exhibit C.

21. Due to the successful testing of the present invention by Daimler-Chrysler as described above, Daimler-Chrysler currently has plans to use the present invention in at least one of its production plants.

22. A current marketing brochure describing the present invention is attached hereto at Exhibit D.

23. The Society of Manufacturing Engineers also published a paper of ours describing the present invention, entitled "The Finishing Line, Inductive Sensor System for Evaluation of Burrs and Edges in Industrial Applications", Society of Manufacturing Engineers, Vol. 21, No. 1 (First Quarter 2005).

24. In sum, the present invention has satisfied a long felt need in the industry by overcoming various problems in the prior art that have not been solved by others. In doing so, the present invention has been warmly received and won awards in the industry.

We hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that all statements made herein are made with the knowledge that the making of willfully false statements and the like is punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and may jeopardize the validity of the application and any patent issuing thereon to which this verified statement is directed.

Manfred Iasiella — Dated: January 31, 2005

Dr. Sorin Fericean — Dated: January 31, 2005

EXHIBIT A

7[th] International Conference on Deburring and Surface Finishing CODEF
University of California, Berkeley, California/USA
June 7-9, 2004

INDUCTIVE SENSOR SYSTEM FOR EVALUATION OF BURRS AND EDGES IN INDUSTRIAL APPLICATIONS

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ABSTRACT

The paper presents the theoretical aspects regarding the first inductive sensor systems for evaluation of burrs and edges of metal work pieces, as well as practical examples and results achieved by the first field tests. The inductive burr sensor system of Balluff received the Award Autotec 2003 as the best innovation in automotive technology (www.autotec-aktuell.de) in Germany, and is also a winner of the R&D100 Award for the year 2003 (www.rdmag.com) in the USA.

I. INTRODUCTION

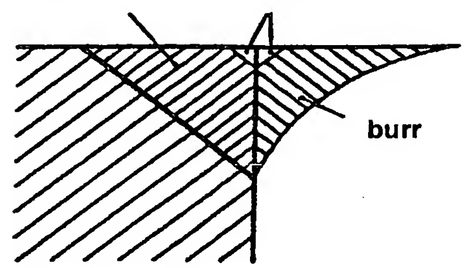
A burr often results by cutting or machining workpieces. The intensity of the burr formation depends, among other things, on the tool geometry (a drill, for example), the machining parameters, and the composition of the workpiece. The degree of burr formation can also change during series production of parts. Burrs present a number of problems. On one hand, there is a risk of personal injury, and on the other hand, burrs on parts used in motor vehicle transmission parts, for example, can affect the flow of oils and fluids or break off and cause premature wear. For these reasons a great deal of expense is devoted to deburring measures. When the parts are quality-relevant, additional costly manual quality control measures have to be performed to ensure that the workpieces have truly been fully deburred. This is extremely difficult in the case of internal bore overlaps. The costs involved in deburring and manual burr inspection can significantly increase the ultimate cost of the parts.

To date, there has been no universal, industrial-suited measuring system for quantitative assessment of internal burrs that can be integrated into production processes. In order to address the problem of burr minimization, in 1999 the "Burr Minimization" industry workgroup of the automobile industry was formed. Members of this workgroup include leading automobile manufacturers as well as scientific institutions. In 2001, Balluff GmbH was invited to the workgroup as the sensor specialist, with the goal of developing an industrial measuring system that would be commensurate with the technical challenges. In the present paper, an introduction into the subject of burr formation will be followed by a description of the theoretical background of the developed solution as well as functional testing and integration of the inductive testing system into the industrial manufacturing process.

II. FUNDAMENTALS OF BURR FORMATION

Definition and characterization

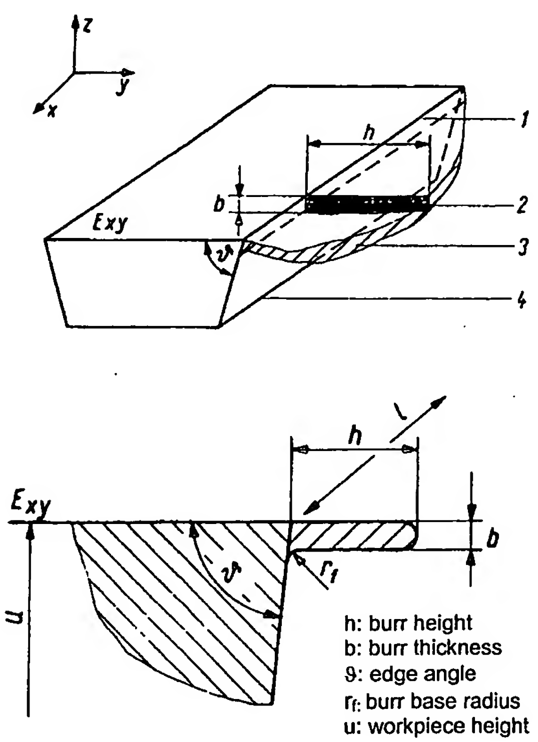
DIN ISO 13715 defines a burr as "an overhanging, sharp workpiece edge" or as "a rough tear of material on an edge which remains after the mechanical processing or forming process" (Fig. 1). Furthermore, with respect to burr heights on stamping, DIN 9830 describes a burr as a generally thin, sharp workpiece overhang in a cut edge.



1. EDGE CONDITION PER DIN ISO 13715.

A comprehensive definition can be found in [Beier, 1999]: A burr is a body created on a workpiece surface during the production of a workpiece, which extends over the intended and actual workpiece surface and has a slight volume in comparison with the workpiece, undesired, but to some extend, unavoidable.

In the idealized representation in Fig. 2 the burr at the burr/workpiece contact point is assumed.



2. BURR DIMENSIONS [BEIER, 1999].

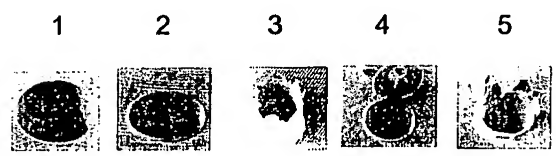
The basic terms are defined in [Beier, 1999]. as follows:

- Burr base profile (1): Geometric size of the presumed straight contact location burr/workpiece surface.
- Burr cross-section (2): Area created through a section vertical to the plane in which the burr base profile lies.
- Burr longitudinal profile (3): Curve resulting from the burr height h.
- Burr location (4): Geometric location of the burr base profile (inner/outer) with respect to the workpiece.

Burr dimensions are defined in Fig. 2.

Classification

From a production standpoint a burr can be classified into 5 various categories (Fig. 3).



3. BURR CLASSIFICATION ACCORDING TO [BERGER, 2002].

The first two types (burr type 1 and burr type 2) are characterized by the defined burr height and by the fact that burrs cannot detach due to their low height. Burrs which break off inside an automobile transmission, for example, can plug oil channels and result in increased wear or failure.

Burr type 3 results typically from dull tools or excessively high feed rates. Rolled burrs formed in many bores for oil channels (hydraulic cylinders, transmissions), can separate and close off the oil channels and are extremely undesirable from a production standpoint.

Rolled burrs such as occur with burr type 4 represent an even greater problem compared to type 3 burr. Burr type 5, the irregular burr, is especially difficult to measure due to its non-uniform structure, which can vary from bore to bore.

III. BURR DIFFICULTIES IN INDUSTRIAL PRODUCTION

Negative impact of burrs

The negative impacts of a burr can be divided into 3 different areas: occupational safety, function reliability, and aesthetics.

From the point of view of occupational safety, burrs on parts represent a potential risk for injury. Burr particles can also result in increased wear or malfunction. This pertains to the production process of the workpiece and the subsequent assembly procedure as well as the use of the end product. If, for example, burrs are formed in bore holes for oil channels, such as in parts for hydraulic cylinders or motor vehicle transmissions, there is a risk that the bore can become partially blocked and result in reduced oil flow. Burrs which separate can have an extremely detrimental effect on the functional reliability and life expectancy of the final product. Nor can those burrs be ignored which may not be problematical from a technical standpoint, but have a negative impact for aesthetic reasons, since they give the impression of low product quality.

Burr Minimization

Research has been ongoing both on the national and international level on predicting and modeling burr formation in metal cutting production processes. Finally, in 1999, the automobile industry tackled the problem formally when it created a workgroup dedicated to burr minimization.

Members of this workgroup include leading automobile manufacturers such as DaimlerChrysler, BMW, VW and Audi along with internally recognized companies and scientific institutes like the Technical University in Berlin, the University of Kaiserslautern, the Fraunhofer Institute, and the University of California at Berkeley.

This workgroup supports new and basic research into burr formation. This support is based on the recognition that burr minimization can succeed only if the essential causal factors are recognized and appropriately addressed. One approach is to define the fundamentals and prerequisites for a practical burr prediction method from relevant experiments that can be reproduced in practice, such as temperature and force measurement or tensile testing, and then to derive burr minimization strategies for tools and technologies [Beier, 1999] An alternate method proposes simulations which allow modeling of burr formation. In addition to burr minimization in drilling operations, software-based optimization of the path of a milling cutter can prevent or at least reduce burr formation on the workpiece [Dornfeld, 2002].

Deburring

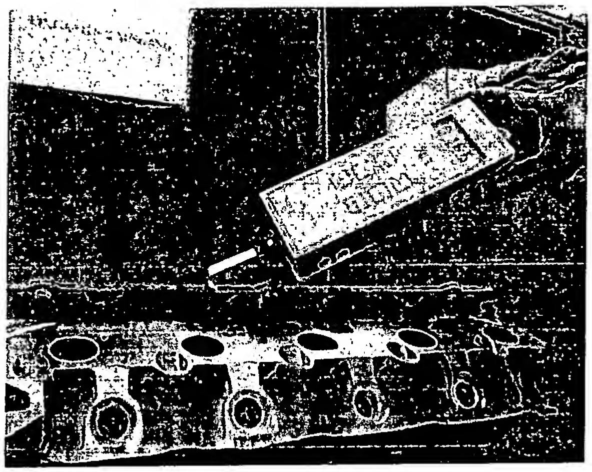
The term deburring applies to all process tasks and methods which are necessary in order to eliminate burrs.. Deburring is an undesirable process from a cost perspective, yet in many cases the negative consequences of burrs make it unavoidable. Parts having low cutting volumes but stringent requirements for absence of burrs may see 20% of the manufacturing cost attributable to deburring. And especially in the automobile industry, an increasingly high power density is demanded. This results in more complex designs with tighter tolerances. In addition, harder, more difficult to machine materials are being used. As a result, the topic of deburring will take on even greater relevance in the future for industrial manufacturing processes. Along with the variety of manufacturing processes in use comes a broad spectrum of burr types. Depending on the material, material geometry, location of the burr and requirements for deburring quality, various deburring procedures that work in different ways have become common. These are described in detail in [Thilow, 1992].

IV. BURR INSPECTION AND EVALUATION

Inspection methods used in industry

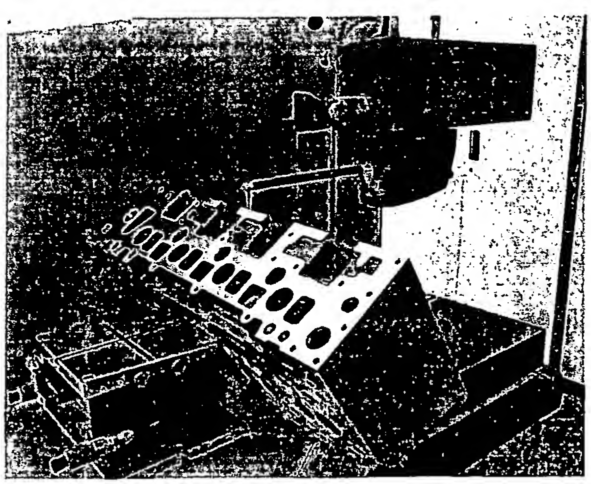
The burr inspection methods used in industrial manufacturing can be divided into two categories, tactile and non-contacting. Tactile inspection involves contact between the probe and the burr. But the resulting force can also affect the burr itself. Using a force transducer as shown in Fig. 4, force can be exerted on the burr

until it either breaks off or bends. The corresponding force can be noted and a decision made as to whether deburring is necessary or not.



4. INSPECTION USING A FORCE TRANSDUCER [BERGER, 2000].

If quantitative statements respecting the burr geometry are required, contour measurement devices (Fig. 5) can be employed. These sense the geometry of an edge by drawing a probe over it. This allows burrs extending up to several millimeters to be measured. The edge radius of the probe itself results in measuring errors at fine resolution levels (> 0.2 mm).



5. CONTOUR MEASUREMENT [BERGER, 2000].

V. BASICS OF THE BURR INDUCTIVE NON-CONTACTING SENSING PRINCIPLE

Applied Electrodynamics Theory

For the specific working conditions of the inductive burr sensor system at very low magnetic field strength, the components of the system including the workpiece with or without burrs can be considered as isotropic, continuous and linear so that Maxwell's equations [Griffith, 1989] may be simplified:

$$\mathrm{rot}\,\mathbf{H} = \mathbf{J} + \frac{d}{dt}\mathbf{D} \qquad \text{(Ampère's law) (1)}$$

$$\mathrm{rot}\,\mathbf{E} = -\frac{d}{dt}\mathbf{B} \qquad \text{(Faraday's law) (2)}$$

$$\mathrm{div}\,\mathbf{B} = 0 \qquad \text{(no name) (3)}$$

$$\mathrm{div}\,\mathbf{D} = \rho \qquad \text{(Gauss's law) (4)}$$

where the vectors **H, B, E** and **D** represent the magnetic field strength, magnetic flux density, electric field strength and electric field density, respectively. The sources are the vector **J** representing the density of the conduction current and the scalar ρ giving the density of electric charges.

In isotropic mediums the vectors **B** and **H** are parallel each to other and the vectors **E** and **D** are also parallel each to other; in linear mediums they are also direct proportional each to other. These properties of the isotropic and linear mediums are described by the material equations:

$$\mathbf{B} = \mu \cdot \mathbf{H} \qquad (5)$$

$$\mathbf{D} = \varepsilon \cdot \mathbf{E} \qquad (6)$$

where μ is the magnetic permeability of the medium and ε is the electric permittivity.

According to Equation (1) AC-currents and/or DC-currents flowing through metallic parts generate a solenoidal magnetic field. In contrast, only magnetic AC-fields having a time variation will induce an electric AC-field (2). Equation (3) stipulates that the total magnetic flux through a closed surface is always equal to zero, so that the magnetic field lines are closed. According to Gauss's law (4), the total electric flux through a

closed surface depends on the contained sources, and the electric field lines are not closed. These physical interpretations of fundamental Maxwell's equations make possible the understanding and the modeling of the phenomenon which characterize the behavior and the operation of the inductive burr sensor system.

Several methods of solving the Maxwell's equations are known. A modern topical procedure uses an auxiliary theoretical vector **A** called magnetic vector potential and defined by:

$$\mathrm{rot}\,\mathbf{A} = \mathbf{B} \tag{7}$$

If the equation (7) is inserted into (2) the result is:

$$\mathrm{rot}\left(\mathbf{E} + \frac{d}{dt}\mathbf{A}\right) = 0 \tag{8}$$

which shows that the field **E** + d**A**/dt is a non-solenoidal field and therefore can be considered as the gradient of a scalar function φ according to the equation:

$$\mathbf{E} = -\mathrm{grad}\varphi - \frac{d}{dt}\mathbf{A} \tag{9}$$

The scalar function φ is called scalar potential. The equations (7) and (9) can be applied in Maxwell's equations (1) and (4). With simultaneous consideration of the material equations and of the Lorentz convention two independent equations result for the potential values:

$$\Delta\,\mathbf{A} - \varepsilon\cdot\mu\cdot\frac{d^2}{dt^2}\mathbf{A} = -\mu\cdot\mathbf{J} \tag{10}$$

$$\Delta\,\varphi - \varepsilon\cdot\mu\frac{d^2}{dt^2}\varphi = -\frac{\rho}{\varepsilon} \tag{11}$$

If the sources of any system to be solved are known and the electromagnetic properties of this system, represented by the parameters μ and ε, are specified, equations (10) and (11) can be solved for **A** and φ. If these primarily quantities are already known, there is no difficulty in obtaining the solution **B**, **H**, **E** and **D** by using the previous univocal equations (7), (5), (8) and (6). The method is universal and can be used for the analytical analysis of above mentioned systems, independent of their complexity.

A significant simplification can be made if the system sources are harmonic time functions. This hypothesis is valid also for the electromagnetic system of the burr sensor, which is supplied by harmonic excitation. In this case the vectors and scalars having the general expressions:

$$\mathbf{X} = \mathbf{X}(\mathbf{p};t) \quad \text{and} \quad \phi = \phi(\mathbf{p};t) \tag{12}$$

where the variable t represents the time and **p** is the current point vector - are harmonic functions with the angular frequency ω:

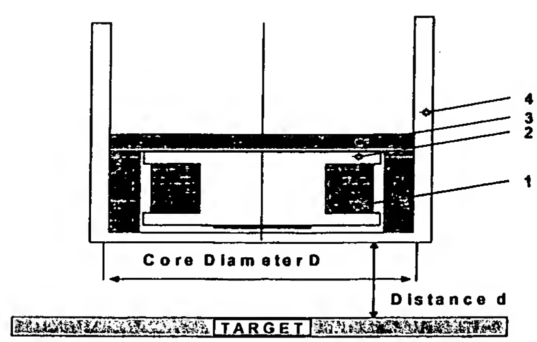
$$\mathbf{X} = \mathbf{X}_{\max}\cdot\mathrm{Re}\left\{e^{j(\omega t+\alpha)}\right\} \tag{13}$$

For this particular case the variable time can be eliminated in (10) and (11) so that the final solution only describes position dependencies:

$$\Delta\,\mathbf{A} + \varepsilon\mu\omega^2\cdot\mathbf{A} = -\mu\cdot\mathbf{J} \tag{14}$$

$$\Delta\,\varphi + \varepsilon\mu\omega^2\cdot\varphi = -\frac{\rho}{\varepsilon} \tag{15}$$

We used this method for the computer aided analysis of the PTBS (primary transducer of the burr sensor), which is an electromagnetic system having medium complexity. The representative structure of the PTBS is schematically illustrated in Fig. 6.



6. TYPICAL STRUCTURE OF THE PTBS
(1) COIL, (2) PLASTIC COIL BODY,
(3) FERRITE POT CORE, (4) PLASTIC CAP.

The essential element is a coil (1) made of massive copper conductor and placed in a ferrite pot core (3). The other mechanical components, e.g. the plastic coil body (2), and the plastic cap (4) with its sealing function, do not play a significant role in the system operation but do strongly influence the system performance. The workpiece to be inspected is figuratively represented by a target plate placed parallel to the active face of the PTBS.

The fundamentals and the phenomenology of the inductive contactless detection are described in detail in [Jagiella, 2002]. Basically the process is based on the electromagnetic damping of the inductive element which belongs to the PTBS. The primary transduction mechanism, i.e. the conversion of the geometrical measurand (shape of the workpiece) into electrical quantity, is a result of the coil excitation by the front-end electronics of the sensor. The complex interference phenomenon between the radiated electromagnetic field and the target finally leads to significant modifications of electrical parameters of PTBS. Paper [Jagiella, 2002] demonstrates that the operation principle is not based exclusively on the eddy-current effect. For middle distances *d* between sensor and ferromagnetic targets, this effect will be suppressed by an additional effect characteristic of variable reluctance sensors relying on gap variation.

From a physical perspective, the PTBS in Fig. 6 is essentially a coil with losses caused by the workpiece having a variable distance *d* to the coil (the evaluated loss) and also by components 1 and 3 (parasitical losses). From the variety of known equivalent diagrams, we have preferred the Jordan serial equivalent type. The quantities of this diagram are the inductivity L and the resistance Rs (the sum of all loss resistances in coil, core, adjacent elements and target) and can be most easily determined by measurements or by the evaluation of simulation results. Consequently, the best way of taking advantage of these physical effects is to evaluate the Q-factor of the PTBS defined as:

$$Q_L = \frac{\Im \overline{Z}}{\Re \overline{Z}} = \frac{\omega \cdot L}{Rs} \tag{16}$$

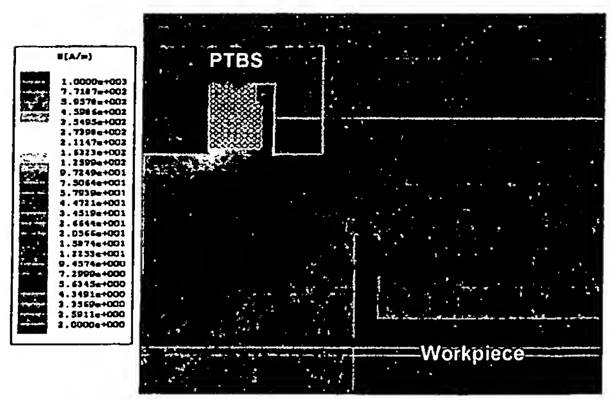
where Z is the impedance of the PTBS.

The field theoretical consideration and the electrical consideration can be joined so that the Q-factor of the PTBS can be displayed in terms of field quantities:

$$Q_L = \frac{\sum_{i=1}^{n} \mu_i \iiint_i \mathbf{H}_i(\mathbf{p}) \bullet \mathbf{H}_i^*(\mathbf{p}) dv}{\sum_{i=1}^{n} \frac{1}{\sigma_i} \iiint_i \mathbf{J}_i(\mathbf{p}) \bullet \mathbf{J}_i^*(\mathbf{p}) dv} \tag{17}$$

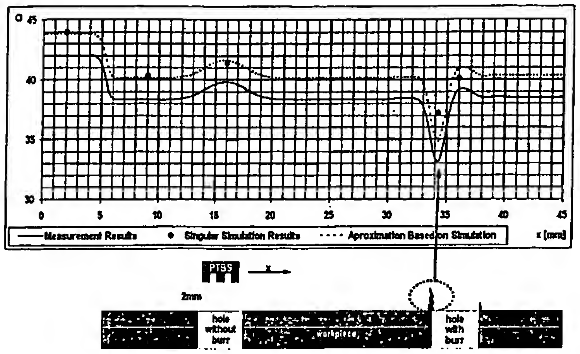
The advantage of equation (17) consists in the possibility to calculate the Q-factor of the PTBS using the field quantities, which can be provided by simulation procedures and to optimize the topology of the PTBS before realization and measurements.

We successfully used this "top – down" design of the PTBS. The field analysis and the model optimization have been made by using an appropriate simulation program [Ansoft, 2002]. The increased number of finite elements allowed a higher accuracy by solving equations (14) and (15). For illustration, Fig. 7 shows the magnetic field in the active zone of the PTBS in a two-dimensional representation. The workpiece having a hole with standard burr topology can be observed.



7. SIMULATION RESULTS: ASPECT OF THE MAGNETIC FIELD FOR A WORKPIECE WITH REGULAR BURR.

After the realization of the already optimized PTBS, the Q-factor was measured and compared with the simulation results. The blue curve of the graph shown in Fig. 8 represents the measured variation of the Q-factor of an optimized PTBS, resulting from its translation



8. COMPARISON BETWEEN MEASUREMENT AND SIMULATION RESULTS OF THE Q-FACTOR VARIATION FOR AN INVESTIGATED STEEL WORKPIECE

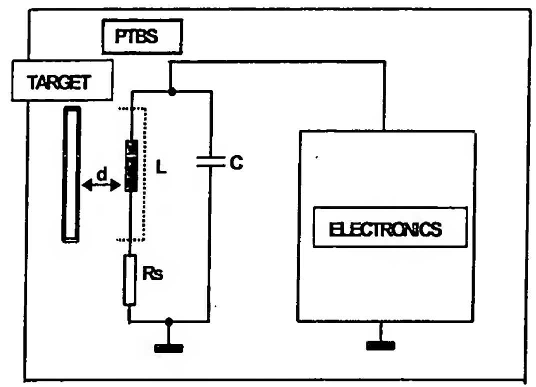
parallel to a steel workpiece, having one hole without a burr and another hole with a burr. The electromagnetic damping effect caused by the flat metal surface, or more strongly, by the burr, leads to a decrease in the Q-value. In contrast, the holes reduce the electromagnetic damping reflected in the diagram by the positive increasing peaks of the Q-value. The simulation results of the Q-value for the significant positions of the PTBS relative to the workpiece shape are represented by the dots. Good agreement between measurement and simulation results can be observed. The offset is motivated by the tolerances of the material specification.

Designed and Implemented Electronics

After the design and optimization of the PTBS, the task was to develop a very high-performance electronics to evaluate the Q-factor and to convert these values into a first intermediate electrical signal of the burr sensor.

For the measurement of the Q-factor of the PTBS and for the conversion into its dependence on the burr we chose to incorporate the primary transducer in a parallel resonance circuit (Fig. 9) and to supply it at its resonance frequency using an original oscillator conceived for this purpose. Basically the PTBS represented in Fig. 9 by the Jordan serial equivalent type diagram (the inductivity L and the resistance R_S) is connected in parallel to the capacitor C. The resulting resonance circuit oscillates with a frequency determined by the parameters L and C. The oscillation amplitude is proportional to the electromagnetic damping caused by the target. The dipole oscillator symbolized in Fig. 9 by the electronics stage maintains steady state oscillations.

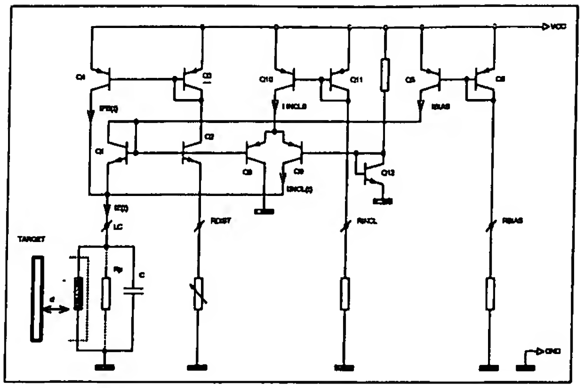
Based on Balluff's experience in the field of the inductive proximity detection, we decided to excite the PTBS and evaluate its Q-factor by using a very high-performance oscillator, known as the oscillator with negative resistance. The operation principle, the circuit description and its advantages are described in [Fericean, 2001]. The major improvements relative to the classical version are shown in [Fericean, 1996].



9. EQUIVALENT DIAGRAM OF THE PTBS CONNECTED TO THE PRIMARY. ELECTRONICS

Fig. 10 shows a simple, high-performance version of this oscillator with negative resistance, which can be realized in either discrete or integrated bipolar technology. The series resistor R_S has been transformed into a parallel resistor R_P. The signal at the connection LC represents the oscillator output signal and has a proportional dependence on the workpiece topology. Ultimately, this voltage is the primary result of the conversion from workpiece topology to electrical signal, and will be used in the burr sensor for the final conversion into the burr sensor output signal.

The functional block diagram of the burr sensor is shown in Fig. 11. The front-end circuit has been integrated into an Application Specific Integrated Circuit (ASIC). The core of this part consists of an improved, very high performance oscillator followed by a precision rectifier.



10. ILLUSTRATION OF AN OSCIL LATOR USED FOR THE EXCITATION AND EVALUATION OF THE PTBS.

This stage converts the above mentioned oscillator output signal into DC voltage which represents the intermediate electrical burr sensor signal. The rectified signal, corresponding to the amplitude of the oscillator output voltage, is fed to the analog ASIC output. This ASIC output signal will be applied to an output driver which provides the final signal conversion and the sensor protections. The front-end ASIC also includes the integrated circuit for the linearization of the sensor characteristic. This compensates in the sensing range of the sensor the exponential gradient of the loss resistance R_P, by using a suitably adjusted reciprocal gradient of the excitation current [Fericean, 1996]. The final result is a linear relationship with the distance *d* over a wide range.

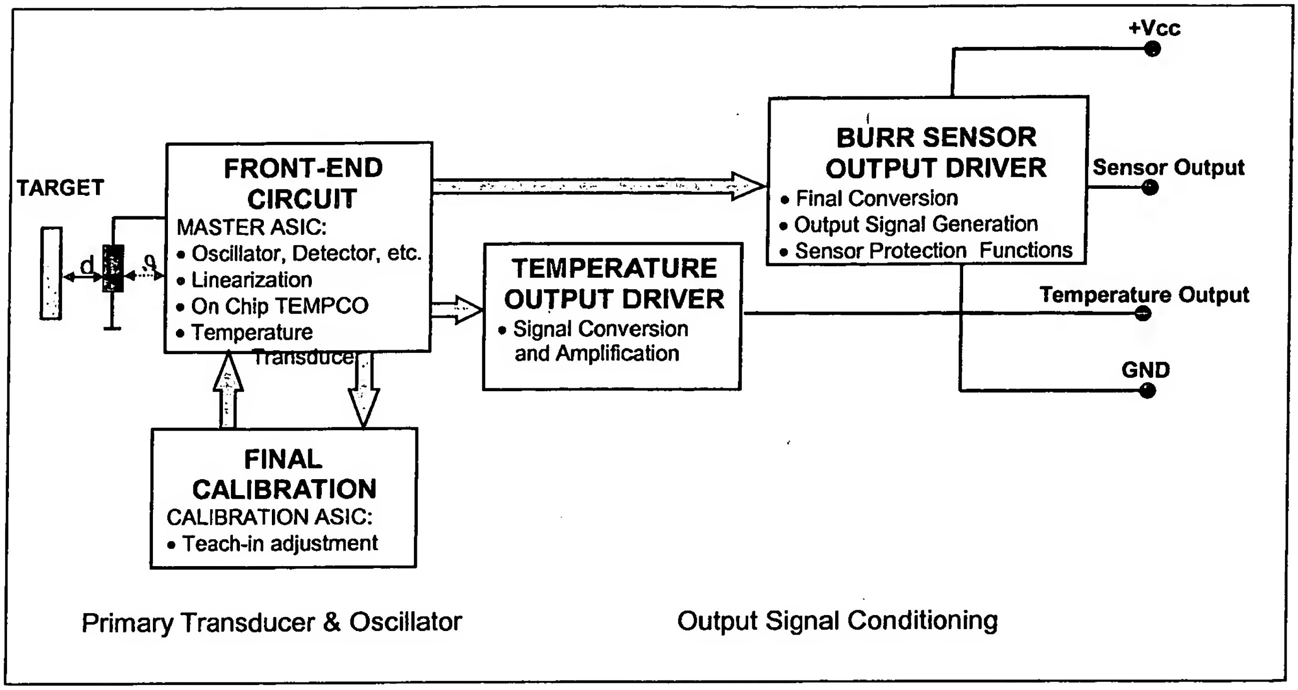
In addition to linearity, the temperature behavior has also been optimized. This is mainly a function of the temperature drift of the sensor element, i.e., the resonance resistance of the coil R_P. The temperature coefficients of the other system components are only of secondary significance. It is critical that the oscillator electronics compensate this temperature drift over a very wide temperature range. The compensation is divided into two steps. In the first step the existing temperature behavior of the PTBS is minimized by an adequate setup of the oscillator electronics.

The second step consists of active temperature compensation accomplished by the oscillator electronics. Here, an integrated compensation stage is used to linearly compensate the coil temperature drift over the entire temperature range. Additionally, nonlinear compensation at the extremes of this range is also possible. These two functions are implemented using a temperature-dependent current source which adds a compensation current to the excitation current [Jagiella, 2003].

This integrated compensation stage offers great advantages over traditional approaches using temperature-dependent resistors. Since the oscillator, linearization and temperature compensation are implemented on a single chip and the latter is located directly next to the sensor coil, the temperature gradients between all components are small. Sample-to-sample differences of the compensation current are lower by several magnitudes compared with the tolerances of temperature compensation resistors.

On the other hand, the integrated temperature sensor of the compensation stage can be used externally for temperature measurements and additional temperature compensation tasks in applications with the burr sensor. The temperature output driver provides an amplification and conversion of the original signal and delivers a second signal of the burr probe.

Due to tolerances which are inevitable in series production, each burr sensor must be individually calibrated. For this purpose, a second ASIC will be used to determine the sensor output characteristic by calibrating the oscillator amplitude using a standard target. A programmable resistor network integrated into the calibration ASIC, whose value is continuously varied after the calibration procedure starts, is changed until the output characteristic of the burr sensor is achieved. Finally, the required resistance value is stored in the EEPROM of the calibration ASIC. Calibration of the finished assembled sensor is done using the "teach-in" procedure described in detail in [Fericean, 1995]. This allows the entire sensor system to be calibrated in a single step; there is no need for cost-intensive, repetitive calibration. All the parameters that affect the oscillator amplitude – even the properties of the potting material or the orientation of the sensor element in the housing – are accounted for and compensated in each sample. Communication between sensor and programming unit is in the housing – are accounted for and compensated in each sample.



11. FUNCTIONAL BLOCK DIAGRAM OF THE ELECTRONIS OF THE BURR SENSOR

VI. REALIZATION OF THE INDUCTIVE BURR SENSOR SYSTEM

Operation and Structure

The burr sensor system under present discussion consists of a burr probe and associated processing unit. The main components of the probe are a metal tube shaped like an endoscope with an active head in the front section and a flange used for fixing the probe. Depending on the application, the active head contains up to 3 inductive heads and the associated electronics (Fig. 12).

The block diagram for the probe electronics with one head is shown in Fig. 11. The active head is supplied with power by the processor and provides several conditioned signals (0 ... 10 V). The main output signal is the burr signal, whose amplitude is a function of the damping of the inductive measuring head, thus providing information about the geometric characteristics of the burr. The electronics in the active head simultaneously make continuous temperature measurements; the conditioned output signal from the temperature sensing section represents a second probe output signal, and is used for monitoring temperature during the burr sensing process. To prevent collisions between the probe and workpiece, the probe outputs a third independent touch signal as soon as these components make contact.

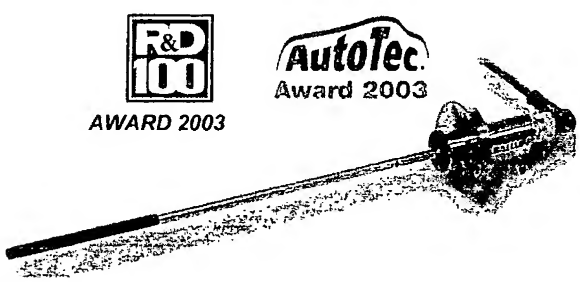
The slender, endoscope-like design of the probe also permits external inspection of the workpieces: evaluation of external burrs, edge assessment, detection of local mechanical peculiarities of the workpiece (bore holes, channels, toothing, etc.), in addition to internal inspection. In the latter case, the probe is introduced into a bore hole where it is able to check through-holes, blind holes, hole intersections, etc., for burrs, threads and dimensions.

In the prototype phase the processor serves as an interface between the burr probe and the host data acquisition system. All primary probe output signals are made directly available to this system (Fig. 15).

Minimal decentralized signal conditioning is performed in the processor. The main output signal from the burr probe is passed to a 4x window discriminator. The capture range of the probe is divided into 4 sub-areas using 3 teach-

in-programmable thresholds. If any given value of the probe output signal lies in a certain range, it is optically displayed in the processor and a switching signal is used to inform the data acquisition system. This function allows programmable classification of the variables, e.g., burrs, under study.

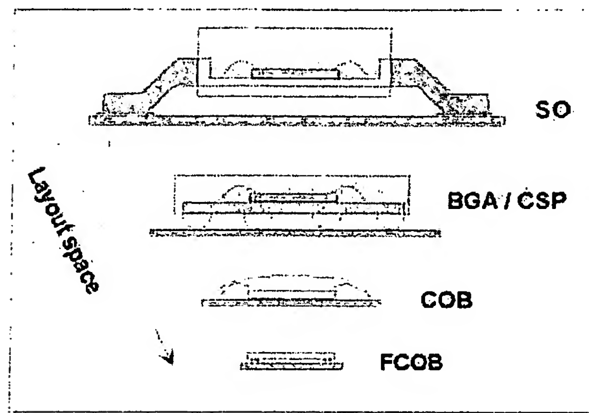
The temperature measured by the probe is also locally monitored. For qualitative assessments of the inspected features of the workpiece, an analog measuring instrument has been integrated, whose input sensitivity can be set to one of 2 ranges.



12. BALLUFF BURR SENSOR SYSTEM PROBE.

Miniaturization

Full integration of multiple measuring heads and the associated sensor electronics into the active head was only possible by miniaturizing the corresponding components. Most of the electronics have been implemented as ASICs, which incorporate nearly all of the sensor functions. The minimal peripheral circuitry consists mainly of external, passive, components, and is used only for determining the ASIC parameters. The master ASIC for the front-end circuit was developed and implemented using a high-frequency, bipolar high-density process. The fine structure enables integration of more than 700 active parts on a silicon surface of less than 4.5 mm^2. For the calibrating ASIC, a compatible low-voltage and low-current CMOS technology was used. This ASIC contains analog stages, an EEPROM chip and a complex state-machine for the teach-in procedures. Miniaturization of the burr probe is also motivated by the huge advances in manufacturing technology. 15 years ago the use of surface mount technology was the optimum means of manufacturing sensors with integrated electronics. Miniaturization was limited by the size of the small outline (SO) ASIC housing. Smaller housings were achieved using Ball Grid Arrays (BGA), whereby the contact area is located beneath the housing. To attain even smaller dimensions, it was necessary to eliminate housings and place the ASIC chips directly on the carrier board.



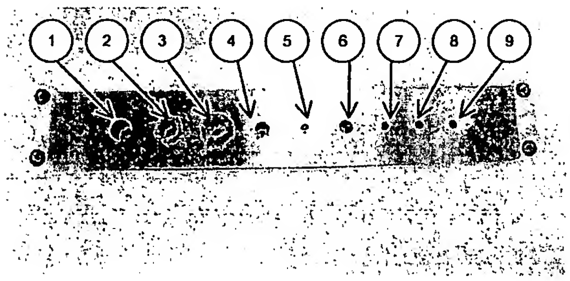
13. STEPS FROM SO TO FCOB.

To make burr sensors with a very small outside diameter, even chip-on-board technology (COB) requires too much room for the connecting wires. The appropriate solution for such highly miniaturized sensors is flip-chip technology (FCOB), Fig. 13. The chip is turned over and attached face down to the carrier board by means of solder points. The diameter of the solder points for the so-called bumps is only approx. 100 μm. The necessary precision for positioning on the circuit board was achieved by using industrial standard equipment, which allows very cost-effective production. The core competence for high product quality with good results focused on the selection of the right filler material between chip and board, and the use of an optimal temperature profile for soldering. Combined with use of passive components in 0402-size, FCOB technology is the method of choice for the manufacture of burr probes with an outer diameter of just 3 mm [Lau, 1996], [Jagiella, 2002].

VII. EXPERIMENTAL AND FIELD-TEST RESULTS

To verify the basic function of the inductive measuring principle, initial experiments were

performed on a test plate. This was prepared with several bore holes of various diameters and defined burr types (Fig. 14).

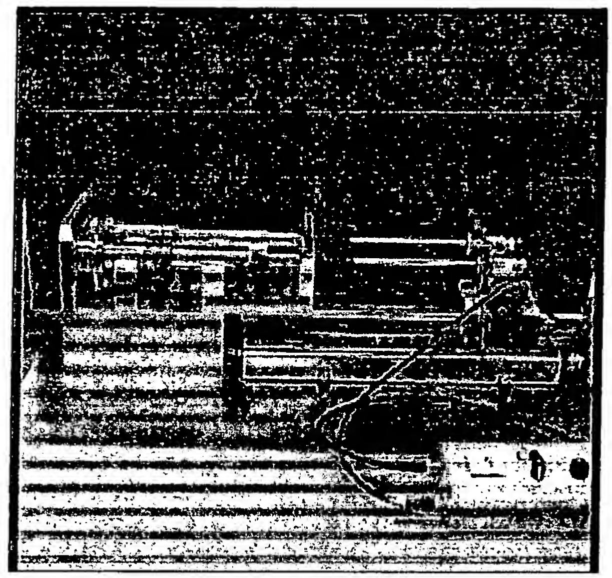


14. TEST PLATE FOR THE INITIAL TESTS.

The measuring procedure was as follows: The burr probe was moved over the bore at a constant distance. The basic distance was set so that no collision with the burrs was possible. A second test plate with identical bore holes but no burr was used as a reference. The measured results showed a clear correlation between the burr sensor output signal and position, which is to say the size of both the burrs and the holes.

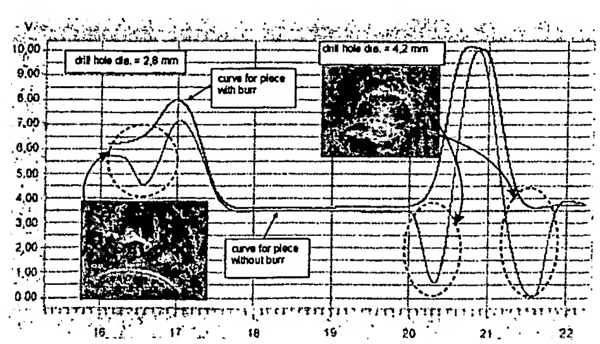
After basic confirmation of the function, an automotive gear shaft was selected as a typical industrial test object. This gear shaft had a longitudinal bore as well as several lateral bores. Located at the intersections between the longitudinal and cross-bore was a burr created during the production process, which is normally removed by a deburring process. A fixture was designed and constructed for the test series. This fixture allows the burr sensor to be introduced into the longitudinal bore of the shaft with high precision. The inductive measuring heads were oriented according to the cross-bore. The data acquisition system detected both the position of the burr sensor relative to the shaft as well as the output signals from the probe (Fig. 15).

Fig. 16 shows a typical result on two cross-bores in the tested shaft. The first curve shows the output-signal for a shaft with deburred exit hole overlaps. The plot of this curve from left to right is interpreted as follows: The sensor first enters on one end of the shaft. The output signal assumes a value which corresponds to the distance between the burr sensor and the wall of the longitudinal bore. The sensor then approaches first bore. The output signal rises, since the material in the active range of the sensor is reduced by the bore. Past the end of the bore, the signal drops to a value which lies below the initial value. This is explained by the fact that the diameter of the longitudinal bore decreases in this area. As the sensor approaches the second bore, a similar curve results. The differences in the signal strength for the second bore are due to its larger diameter.



15. TEST FIXTURE WITH BURR SENSORS, GEAR SHAFTS AND PROCESSING UNIT.

The other plot corresponds to an identical shaft with burrs at the bore overlaps. The first bore has a burr on one side. This is reflected clearly in the signal plot: As the sensor approaches the burr, more material is located in the viewing area of the sensor, which results in a smaller signal.



16. OUTPUT SIGNAL FROM BURR SENSOR.

At the second bore there is a more significant burr both on the left and right. This is reflected in the smaller output signal from the burr sensor. The sensor is thus able to detect both the bore dimensions (increase in output signal) and the intensity of the burr (diminished output signal) with a high degree of sensitivity. By differentiating the measurement signal the influence of the bore can be eliminated, resulting in a plot which correlates highly with the burr intensity.

VIII. CONCLUSIONS

Beginning with fundamentals of the burr and the presentation of the burr difficulties and traditional burr inspection methods in industrial production, the paper continues with the description of the new inductive procedure and sensor system for the contactless burr detection, evaluation, and classification. The paper ends with the demonstration of the very positive results achieved during the field tests in reference production line.

The Balluff burr sensor system integrates automatic burr detection within the production process. The system allows for unaffected part inspection by tough industrial conditions like residues of oil, lubricants, and other contaminants, and eliminates the need for redundant deburring and visual inspection. Thus, part quality in every area of production will be increased, and the part and component yields will be improved. The Balluff burr sensor system increases the production observability and enables the implementation of statistical process control procedures. Finally the integration of the Balluff burr sensor system significantly lowers process cost and improves overall profitability.

The invention is secured by several international patents of the inventors Jagiella - Fericean, and claimed by the company BALLUFF.

The application field could be enlarged by using the system for further tasks, e.g., inspection of workpiece edges, measurement of hole diameters, as well as thread detection inside holes.

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EXHIBIT B


R&D 100

Presented to

BALLUFF

for the Development of

Burr Sensor System

Selected by *R&D Magazine* as One of the 100 Most
Technologically Significant New Products of the Year

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Tim Studt
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1. Preis

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Geschäftsbereich Sensoren

Baden-Baden, 30. Januar 2003

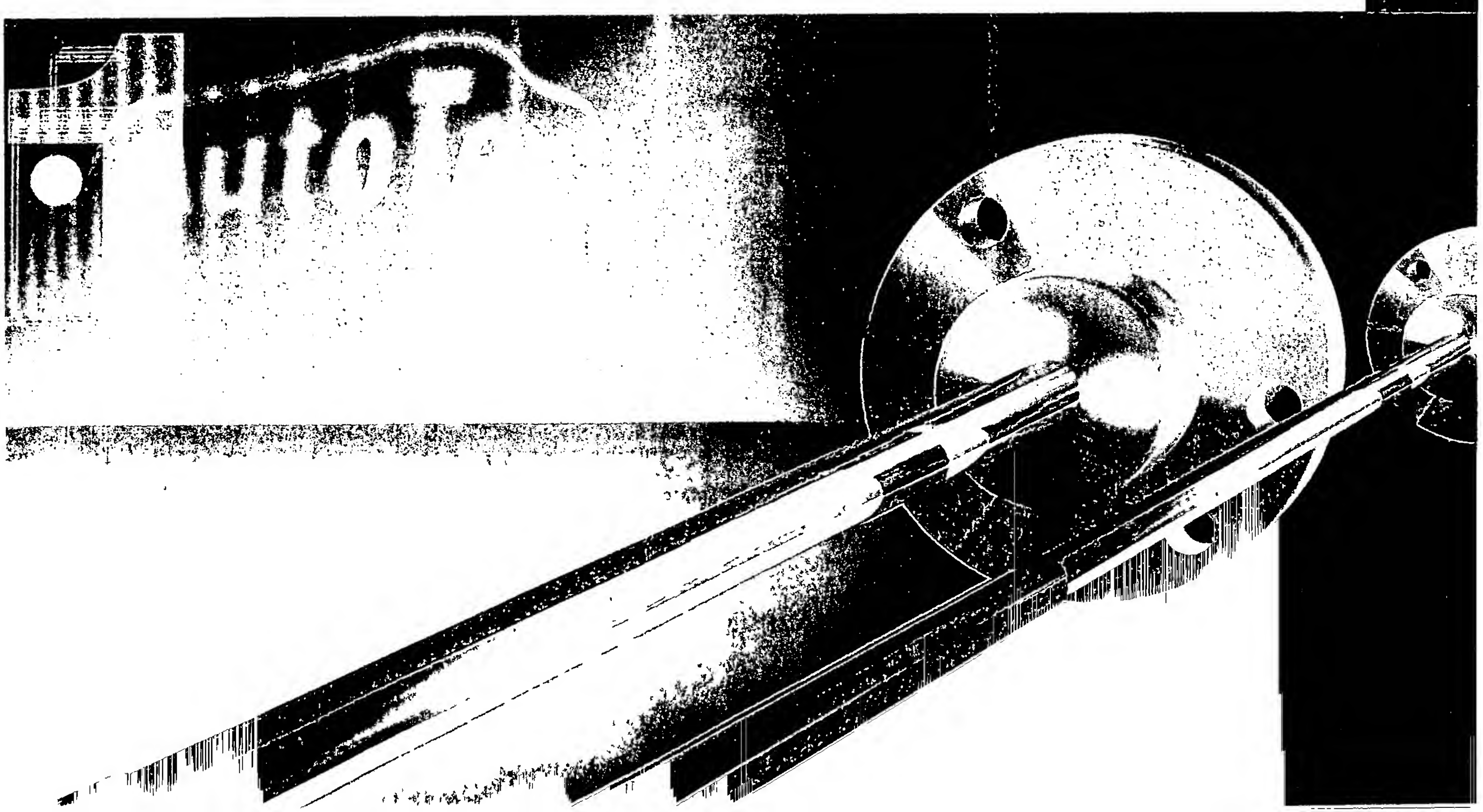
Ina Mrosk
IIR Deutschland GmbH

Matthias Brodrück
IIR Deutschland GmbH

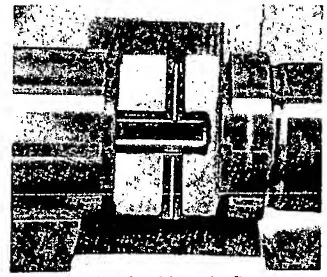
EXHIBIT D

Inductive Burr Probe Project

... awarded 1st prize for innovative automotive technology



Inductive Burr Probe Project



Burr location in drive shaft

A burr is often created during cutting operations in any phase of automobile manufacturing, such as when drilling through-holes in engine blocks or producing drive shafts.

The degree of burr formation depends among other things on the material of the cutting tool (drills, end milling cutters, etc.), on the machining parameters and on the composition of the workpiece and may even vary during series production.

A burr can cause a variety of problems. Burrs may represent a potential for injury during handling, may affect the flow of oil on parts in the drive area or may break off and thus cause premature wear.

For all of these reasons, many parts are 100 % deburred. In the case of many quality-dependent parts (such as injection nozzles in a common rail system), manual quality inspection is additionally required to ensure that the workpieces are truly absolutely burr-free. This is extremely difficult when it comes to interior hole intersections. The costs for deburring and for manual burr inspection can amount to several percent of the cost of the parts.

Up to now there has been no universal, industrial quality measuring system for quantitative assessment of burrs which can be integrated into production processes.

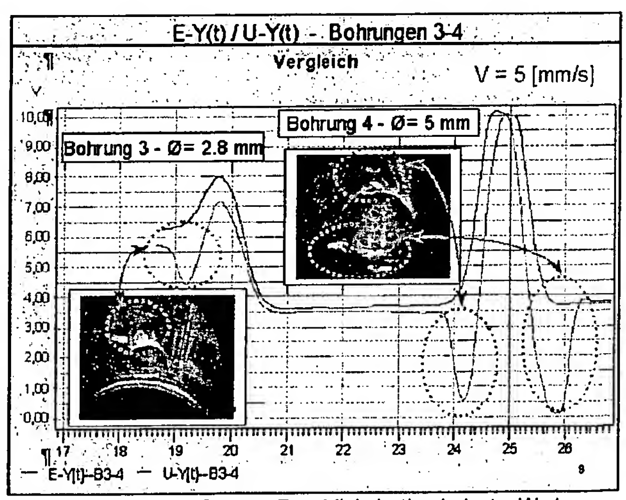
To solve this basic problem, the Burr Minimization Industry Workgroup was founded at the end of 1999. In 2001, Balluff GmbH joined this Workgroup with the goal of developing a measuring system which would meet the requirements outlined above. After some framework studies, a unique inductive measuring system was soon developed, which is currently in the prototype stage and which has already passed the first round of practical tests in the automobile industry.

In addition to burr sensing, this rugged sensor system can be integrated into metallic workpieces in industrial production systems for general edge and geometry measuring purposes. The probe is ruggedly constructed, and the measurements are unaffected by oil, lubrications and contamination.

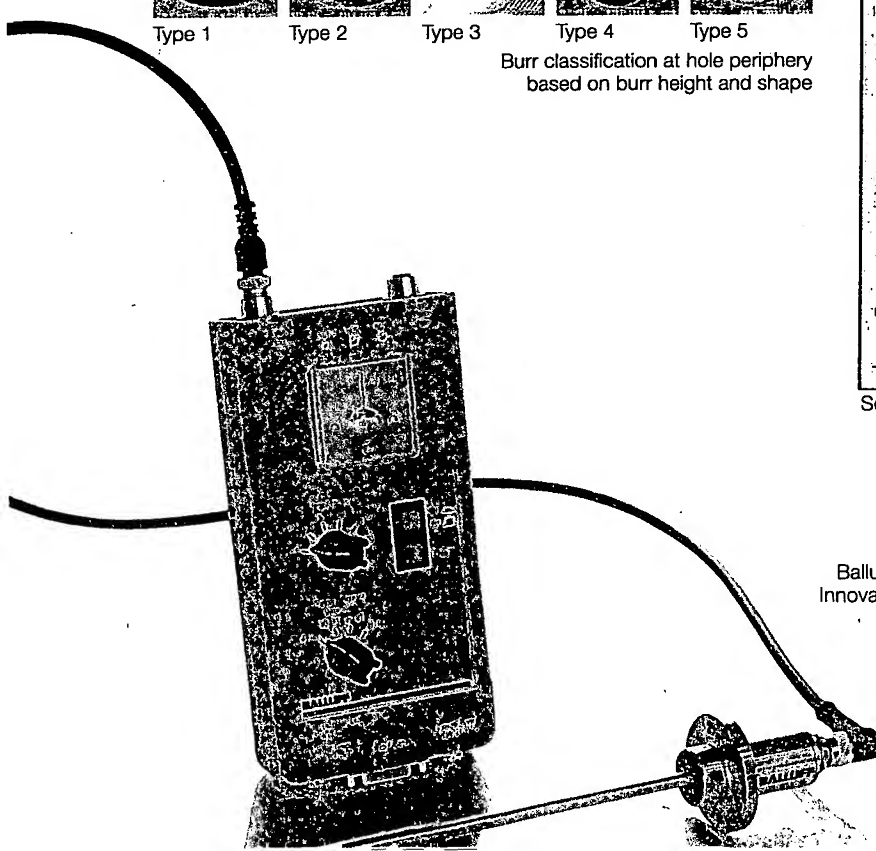
This makes the system easy to integrate into industrial production areas without impacting the cycle times.

Use of the measuring system will increase part quality levels in every area of production. Trend analyses make statistical process control possible and allow significant cost savings.

Burr classification at hole periphery based on burr height and shape



Sensor signal Source: Burr Minimization Industry Workgroup



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